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Determination of Detonation Parameters of Booster Explosives at Small Charge Diameters

Robert J. Spear and Michael G. Wolfson

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Abstract

An experimental method for determining velocity of detonation (VOD) of unconfined explosives at small charge diameters has been developed. The experimental technique uses readily available components and is relatively easy to set up. VOD is measured by ultra-high speed streak photography; variation in magnification on the streak record has been detected. VOD was determined on conventional booster explosives based on RDX/polyethylene wax (PEW), DNBF, and two candidate insensitive booster explosives PBXW-7 and ADNBF. All were pressed to 80-95 %TMD (theoretical maximum density), and diameters ranged from 12.75 mm to 1.52 mm. A surprisingly strong dependence between the critical diameter (d_c) estimated from these firings and %TMD was observed. It is suggested that further measurements should be made for explosives pressed to 80-95 %TMD, which is typical of production filling and where only very limited data are available. Comment is made on the potential of PBXW-7 and ADNBF to replace conventional booster explosives in fuzes for insensitive munitions.

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Determination of Detonation Parameters of Booster Explosives at Small Charge Diameters

1. Introduction

There is a growing awareness throughout the Western military community of the operational benefits of insensitive (low vulnerability) munitions (IM). A variety of policies have been adopted or are under active consideration; included here is Australia, where the Australian Ordnance Council (AOC) is currently formulating a position paper [1] for consideration by the Australian Services in early 1990.

The US Navy (USN), which has the most advanced IM policy [2] is adopting as its primary approach to meet its IM criteria [3, 4], the development of less sensitive explosive and propellant fillings. In the case of warheads, the main R & D thrust has centred on cast-cured polymer bonded explosives (PBXs) as main-charge fillings [5]. The replacement of current melt-cast TNT-based explosives by cast-cured PBXs has in general resulted in US IM criteria being met.

However, these advances in main charge fillings can only be partially realised while other elements of the explosive train, particularly the fuze booster, still consist of high vulnerability fillings. For example, a high order cook-off response from the fuze booster will cause detonation of remaining, unburnt, PBX main-charge. Consequently, there are active R & D programs both in Australia [6, 7] and overseas to develop booster explosives that meet IM guidelines.

There are strict performance requirements for insensitive main-charge fillings such as cast-cured PBXs; the USN has a general requirement that insensitivity will be achieved without performance reduction relative to currently used (non-IM) fillings [3]. An

insensitive booster explosive must meet even more tightly defined criteria. In particular, parameters such as detonation velocity (VOD) and pressure must be at least equal to currently used explosives such as tetryl, while shock sensitivity cannot be unduly sacrificed and detonation pickup and function must occur reliably for relatively low masses in small diameter channels.[1]

The study reported here describes development of a method for assessing two aspects of the performance of candidate insensitive booster explosives; the VOD/charge diameter relationship, and the critical (failure) diameter below which stable detonation cannot be sustained. Both these parameters are dependent on charge density. The method is of course applicable to currently used booster explosives, and other more sensitive explosives which are required to function reliably in small geometries. Critical diameters of booster explosives are typically less than 3 mm at the densities used in fuzes [8a].

Development of the method was initially undertaken on some RDX/polyethylene wax (PEW) explosives, RDX/PEW 99.6:0.4 to 94.6:5.4 [9], which are typical of currently used booster explosives. Using the method developed for these formulations, parameters were then measured for PBXW-7 Type II (RDX/TATB/Viton A 35:60:5), which has been proposed as an insensitive booster explosive for the USN [10]. Parameters were also determined for 4,6-dinitrobenzofuroxan (DNBF), a relatively sensitive high explosive [11, 12], and 7-amino-4,6-dinitrobenzofuroxan (ADNBF), an explosive related chemically to DNBF which is currently being assessed in insensitive booster explosive formulations by the USN [12].

2. Critical Diameter and its Measurement

Knowledge of the relationship between performance, e.g. VOD and detonation pressure (P_{CJ}), and charge diameter for a particular explosive formulation at a particular density is important at a number of different levels. As an engineering tool, it is crucial to be able to define the range over which an explosive behaves "ideally"; the limit of non-ideal behaviour is the critical diameter (d_c). As a research tool, two-dimensional effects, especially near the critical diameter, are important probes into the structure of the explosive reaction zone.

As a consequence, diameter dependence of VOD and d_c have been extensively studied, particularly by Russian scientists [13, 14]; relevant Russian references are cited in [15]. A compilation of d_c values for a range of explosives has been published [8a]. Data on pressed explosives selected from this reference and other literature sources [16-27], together with some other types of RDX formulations, are listed in Table 1.

A major gap in the published data, evident from Table 1, is for explosives pressed to 80-95 %TMD (theoretical maximum density), which is the density range covering most booster explosives which are pressed in ordnance production. The US data in general are for explosives pressed to near crystal density (100 %TMD) [16, 18, 19, 21, 23] while Russian [13, 15, 17] and other [24] data are often for densities around 1.0 Mg/m^3 (50-60 %TMD). Because RDX formulations were used in the present study to develop the experimental

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1 System design or redesign for an existing fuze can alleviate some of these constraints.

method, data for cast-cured RDX/binder [25] and extruded plastic explosives [26, 27] are included for comparison in Table 1.

Determination of d_c on unconfined charges is relatively straightforward on materials such as melt-cast TNT formulations, which typically have $d_c > 6$ mm [28]. A reasonable estimate of d_c can be obtained from a conical charge with a very narrow cone angle [29, 30], or a stepped charge consisting of a series of cylinders of decreasing diameter [16, 30]. Both these types of charges can be readily prepared by casting melt-cast TNT-based explosives or cast-cured PBX [31] in appropriate moulds, and subsequently machining to size if required. Both these methods tend to underestimate d_c, i.e. give estimates lower than that required to sustain stable detonation in a cylindrical charge, because the shock is overdriven from the larger diameter.

Following estimation by one of the above methods, an accurate measurement of d_c, and of VOD as a function of diameter, requires a series of measurements on charges of fixed diameters. Again this method is most easily carried out on cast charges that have larger critical diameters and can be readily machined to size. Pressed charges are more difficult to study because of their typically small d_c (Table 1), while at diameters close to d_c failure may not occur until a considerable distance beyond the initiation point; failure of confined nitromethane has been observed to occur after 11 charge diameters [32] while unconfined PBX-9502 (TATB/Kel F-800 95:5) has failed at -55°C after 25 charge diameters [19]. In addition, minimisation of density gradients requires that pressed pellets not exceed length to diameter ratios of unity. Because of these two requirements, test charges must consist of a stack of accurately aligned and tightly held cylindrical pellets. Although confining the charge overcomes some of these problems, confinement can have appreciable effects, making comparison difficult, while other problems are also introduced [33]. We have previously described a miniature ionisation probe technique using a multilayer circuit board which is suitable for confined, short, small diameter charges [34].

In 1955 Campbell et al [35] described a method for determining d_c using stacked cylindrical pellets, and further elaborated on the method in 1976, including experimental determinations for a number of explosives where d_c was less than 2 mm [18] (see Table 1). However a number of the explosives were required to be machined to obtain the necessary precision and while this could be done for PBX-9502 [19] and related explosives [18, 23] at these high densities it was inappropriate for booster explosives at the densities we wished to study.

We therefore set out to develop a method which was relatively simple to set up and readily applicable for small diameter pellets at densities of 80-95 %TMD. In essence it is a modification of the Campbell technique [18, 35] using a simpler method of holding the cylindrical pellet stack. Velocities were determined by ultra-high speed streak photography rather than ionisation probes, primarily because the manufacture of small ionisation probes and their assembly into a stack of small diameter pellets would be extremely difficult. In addition such probes can disturb the detonation front [18] and, under marginal conditions near d_c, this disturbance could be sufficient to cause detonation failure.

3. Experimental

3.1 Materials

RDX/PEW formulations 99.60 : 0.40, 97.82 : 2.20, 97.15 : 2.86, 95.33 : 4.69, 94.59 : 5.39 were prepared in a previous study [9] and they are the same batches described in that report.

PBXW-7 Type II was Batch NSWC ID#579, obtained from Naval Surface Warfare Center, Whiteoak, MD, USA. Further descriptions and characterisation have previously been published [36].

DNBF was prepared by nitration of benzofuroxan (Aldrich Chemicals) and recrystallised from ethyl acetate as described by us previously [11].

ADNBF was prepared by nitration of chlorobenzofuroxan followed by reaction with ammonia as described by Norris [12], and recrystallised from ethyl acetate.

3.2 Preparation of Pressed Pellets

Pellets of nominally 12.7 mm diameter were prepared by pressing to the required density in a hardened steel mould using an Instron Universal Testing Machine operated as a press. Full experimental details have been published previously [37].

Smaller pellets, diameter 6 mm and less, were prepared by pressing in steel moulds using an Eltor press with the load required to achieve the particular density.

Densities were determined by accurate weight and dimensional measurements. Pellets were weighed on a Mettler Analytical Balance Model H60 except for very small pellets weighing less than 50 mg, where a Mettler ME 30 Microbalance was used. Dimensional measurements were made with micrometer gauges, and uniformity of dimensions was checked by optical microscopy; chipped and otherwise imperfect pellets were rejected.

3.3 Preparation of Charges for Firing

A special jig was devised to support the cylindrical explosive pellets (Fig. 1), consisting of a rectangular sheet of cardboard about 2 mm thick into which a slot was cut. The slot dimensions varied and were chosen so that an exploding bridgewire (EBW) detonator fitted in at the top without quite falling through and the explosive pellets similarly fitted in the slot below. After fitting the detonator and explosive pellets and ensuring there were no gaps between pellets, a cardboard end stop was stuck across the board in contact with the bottom pellet (see Fig. 1).

Before assembling the detonator and explosive pellets taut horizontal wires were fixed across the slot, one just above the detonator and one just below the end stop. The

distance between the wires was measured with an accuracy of ± 0.05 mm using a Bishop Opto-Scale. The slotted card was then firmly fixed to a wooden base so that the slot was vertical (Fig. 1).

3.4 Firing of Explosive Charges and Recording of Data

The assembled charge was set up vertically in the firing chamber and the firing leads connected, at all times taking care not to bend the card. A Cordin Mod. 330 simultaneous streak and framing camera was used in the streak mode, the streak slit being focussed by back projection vertically along the charge and including the fiducial wires. The camera was loaded with film and then run at low speed while the charge assembly was back illuminated and the camera capping shutter opened for a predetermined time. This exposed silhouette images of the two wires onto the film thus providing fiducial lines along the full length of the film. The film was left in the camera, the lights were removed from the firing chamber, and the camera was then run at a known high speed and the charge fired. This exposed a continuous displacement/time record of light output from the detonation front on the same film used for exposure of the fiducial lines, as exemplified by Figures 2-4.

All RDX/PEW charges were fired in air and produced good streak records on Kodak 2475 photographic film, processed in Microphen for 7 min at 20°C (Fig. 2b). However, the detonation light output from the other explosives tested was not sufficient to produce a good streak record. Consequently they were fired in argon for enhanced light output. This was achieved by fitting a cardboard box over the charge, filling it with argon which was continuously fed in at the bottom of the box and allowed to escape at the top. The box had two parallel transparent Perspex windows facing the camera. When firing the DNBF, ADNBF and PBXW-7 charges in argon, Ilford FP 4 film, processed in DK 50 (1:1) for 6 min at 20°C was used to produce a well exposed image (Fig. 3b).

For a later series of firings all explosive charges, i.e. RDX/PEW, PBXW-7, DNBF and ADNBF, were fired in air. This was made possible by the use of Kodak T-Max P3200 film, a relatively new film which can be exposed for a range of exposure indexes from 800/30° to 12 500/42° by varying the development time in T-Max (1 + 4) developer from 6½ min to 12½ min at 27°C. Good quality streak records were obtained by developing films from the RDX/PEW shots for 7½ mins, and for 12 min for the others (Figs 2a, 3a). It is envisaged that T-Max P3200 film will in future be used extensively in ultra-high speed rotating mirror streak and framing cameras.

Temperature was not controlled during the firings and ranged from about 12-18°C over the entire series. Variations in VOD for the types of charges studied here are known to be small even over a very extended temperature range [19]; the variation from 12-18°C would possibly lead to a maximum change of 25 m/s [19].

3.5 Analysis of Streak Records

VOD was determined by measurement of the gradient of that portion of the streak record where detonation was stable, taking into account the camera writing speed and the magnification of the image. Those portions at the start of a streak record which showed the

explosive was under or overdriven from the EBW detonator were excluded from the measurement.

For analysis, an enlarged print was made from each 35 mm streak record. Two methods of analysis were then employed. In the first, a straight line was marked parallel to and just touching the straight line portion of the streak record. A right-angled triangle was then constructed by drawing one line parallel to and one line perpendicular to the fiducial scale (Fig. 2b). Measurement of these two lines with the Opto-Scale permitted determination of the gradient of the streak line. (This method was found to be more accurate than angular measurement of the gradient.) As the distance between the fiducial lines and the camera writing speed (corrected for non-linearity) are known the gradient can be readily converted to VOD. When constructing the triangle a sharp scalpel and a steel straight edge were used to scribe very fine lines. For measurement, the print was back illuminated by placing it on a light box. The overall measurement accuracy was estimated at ± 30 m/s.

The other method of analysis made use of a Calcomp Mod. 622 digitising tablet interfaced to a personal computer, to digitise an enlarged print of the streak record. After taking account of the image magnification and camera writing speed a distance/time plot was obtained. Any points at the start of a record which visibly did not fall on a straight line were ignored as being indicative of under or overdrive. A linear regression was performed on the remaining points to determine the best straight line fit; the gradient of this line is the VOD.

Although, in principle, digitising the record was the preferred method of analysis the Calcomp Mod. 622 did not provide the required measurement accuracy. Consequently the graphical method first described was used for analysing all the streak records in this study.

4. Results and Discussion

4.1 General Comments

Components for the VOD method can be readily fabricated and with practice are easy to assemble. The cardboard support is cut to the desired dimensions, fiducial wires are attached and then the charges are inserted after the EBW detonator. Naturally it is a fiddly procedure for very small diameter charges, considering that usually 10 to 15 pellets are fitted into the jig to ensure detonation is not fading over the charge length. The smallest diameter charge which was successfully fired was DNBF of 1.52 mm diameter, and stable detonation was achieved. Ten firings of 2 mm diameter charges were carried out; of these only two failed and both are entirely consistent with the trend in the VOD results obtained for these materials at larger diameters and do not reflect failure of the system.

VOD for a series of RDX/PEW formulations, ratios 99.60 : 0.40 to 95.33 : 4.69, at 92.0 %TMD and 12.75 mm diameter, and for the 97.82:2.20 formulation for a range of diameters down to 2.025 mm, are detailed in Table 2. Further VOD/diameter data for RDX/PEWs are shown in Table 3 for 87.3, 88.9 and 95.8 %TMD charges.

VODs measured at a series of charge diameters from 12.75 to 2.02 mm for PBXW-7 Type II pressed to 90.0 and 80.0 %TMD, and some 12.75 mm charges at about 90 %TMD,

are listed in Table 4. Literature data for PBXW-7 (types) are detailed for comparison in Table 5. In Table 6 are listed VODs for DNBF and ADNBF at a range of diameters and a range of %TMD.

It should be noted that discrepancies are apparent in the VOD of apparently identical charges. The most obvious example is PBXW-7 where the three 90.0 %TMD charges of 12.75 mm and 5.91 mm diameter gave VOD with range ±100 m/s from the mean (Table 4). These charges were of excellent quality with exceptionally small density spreads between individual pellets (± 0.001 Mg/m^3, i.e. ~ 0.05 %TMD). Measuring errors from the streak traces were estimated as ± 30 m/s maximum, hence neither can be the principal cause of the variation.

Further investigation was carried out by determining VOD on three 12.75 mm diameter PBXW-7 charges using simultaneous streak and ionisation probe (IP) measurements. It can be seen from Table 4 that all the streak results are higher, but not by a fixed amount, than the IP measurements.

The time base accuracies of the streak camera and the ionisation probe VOD measurement system [38] were verified. Close examination of the streak records revealed a variation in image sharpness across the film (in the space direction). Further testing revealed a variation in magnification across the film of about 9% from edge to edge. This was an unexpected result which is currently being examined more closely. It should be noted that all the VOD results (Tables 2-4, 6) and the estimate of accuracy have been calculated assuming a constant magnification across the film. The variation in magnification seems to be inherent in the camera optics and could account for the higher VODs obtained using the streak method compared with the IP method. It could also account for some variation in results from charges of the same composition, density and diameter.

A preliminary estimate of the inaccuracy due to the variation in magnification across the streak film indicates that the VODs listed in Tables 2-4 and 6 are high by 1-3%. In due course it is expected that the results from the streak records will be individually corrected taking into account the position on the film of that portion of the streak image used for VOD calculation.

Another source of error is the inability to accurately determine the densities of very small diameter pellets (< 3 mm). All pellets are microscopically examined for chips or other imperfections, and discarded if such imperfections are found. Nonetheless, densities on these small pellets can realistically only be determined to ± 0.01 Mg/m^3, i.e. ± 0.6 %TMD. This is an inherent problem for all firings using very small diameter charges, and cannot be overcome by pressing into a container because vertical density gradients are necessarily formed during the sequential pressing operations.

VOD results for the individual explosives are discussed below.

4.2 RDX/PEW Formulations

The first portion of this work was carried out as part of the R & D task on tetryl replacements for Australian ordnance [9, 39]. The main recommendation from this task was that two formulations form the basis of Australian filling operations:

TR1 RDX/PEW 98.75:1.25, for fuze leads and small pellets
TR1SG TR1/zinc stearate/graphite 99.25:0.5:0.25, for auto-pelletting

Most of the early firings were carried out on a 97.8:2.2 RDX/PEW formulation, chosen as a worst case model for TR1SG and a substantial overtest for TR1. The results of these firings have been referred to earlier without giving details [39]. Later firings on a variety of formulations were designed to prove the utility of the VOD/diameter method described here.

VOD for 12.75 mm diameter charges for various RDX/PEW formulations at 92.0 and/or 88.9 %TMD (Tables 2 and 3) are plotted in Figure 5. Although there are only a small number of points, both show the expected decrease in VOD with increasing % PEW (decreasing % RDX).

VODs for the RDX/PEW 97.8:2.2 formulation were determined over a range of diameters and at 95.8, 92.0 and 87.3 %TMD (Tables 2 and 3). The most complete data, for 92.0 %TMD, are plotted in Figure 6 (upper graph) where it can be seen that VOD drops off slowly with diameter till about 3 mm, and rapidly decreases at 2 mm. This is typical of military high explosives [18, 30] where the VOD just above d_c can be only 15% less than that at infinite diameter, and suggests that d_c for the 97.8:2.2 formulation at 92.0 %TMD must be only just below 2 mm. In contrast, at 87.3 %TMD d_c is > 2 mm (detonation failed) and the very low VOD at 3.075 mm (Table 3) suggests that this diameter is close to d_c. The higher density 95.8 %TMD charge propagated with high VOD at charges down to 2.025 mm diameter. The reduction in VOD at 2.025 mm relative to 5.92 mm diameter was only 2.8%, indicating that d_c was probably less than 1.5 mm.

Although these values are only estimates, the magnitude of the variation of d_c with %TMD was surprising, i.e. from ∿ 3 mm at 87.3%TMD to < 1.5 mm at 95.8 %TMD. As discussed in Section 2, most published data for d_c are at very high or relatively low %TMD; more detailed determination could provide valuable insights into the processes occurring during detonation under marginal dimensional conditions, and will be pursued further. On the practical side, detailed consideration must be given to the choice of densities at which TR1 and TR1SG are filled into small diameter leads and pellets. The charges are of course confined in munitions, which will reduce d_c.

In summary, the firings on RDX/PEW formulations confirmed the utility and accuracy of our experimental method. Further firings were then conducted on "insensitive" booster explosives for which only limited data were available.

4.3 PBXW-7 Type II

VOD for PBXW-7 Type II at 90.0 %TMD decreases steadily with charge diameter until failure occurs at 2.02 mm (Table 4 and Figs 4 and 6). At 80.0 %TMD there is a steady decrease in VOD from 12.75 mm to 3.075 mm diameter (Table 4); a firing was not carried out at 2 mm diameter but a failure would have been expected on the basis of the 90.0 %TMD results.

Comparison with published data for PBXW-7 Type I (Teflon binder) [40] and the analogous UK formulations BX1-4 [41] can be made via Table 5. The VOD for PBXW-7 Type I at 90.0 %TMD and 12.7 mm diameter, 7350 m/s, is virtually identical to our data obtained using ionisation probes (Table 4) and strongly supports the conclusions outlined in

Section 4.1 that the VODs obtained by streak photography are increased because of the variation in magnification of the streak image across the film.

A puzzling feature of the published data is that while failure is reported for charges of PBXW-7 Type I at less than 6.4 mm diameter when pressed to 96.95 %TMD [40], Hutchinson [41] observed that 3 mm square x 10 mm length charges of BX1-4 confined in brass all detonated at 86.85 %TMD. Hutchinson's estimation of the critical diameter as below 3 mm for confinement in brass would be consistent with our results on unconfined charges. Perhaps the US failure at 6.4 mm diameter [40] was due to inadequate initiation/boostering.

Comparison of the VOD/diameter relationship for RDX/PEW 97.8:2.2 with PBXW-7 Type II (Fig. 6) suggests that change from a conventional fuze filling (such as RDX/wax) to an "insensitive" filling such as PBXW-7 will involve decrease in performance at small diameters. The obvious conclusion is that it will be difficult to make fuzes less vulnerable to hazardous stimuli by merely replacing current fillings; a penalty in reliability would almost certainly be incurred. Although each fuze type would have to be treated separately, some redesign would most likely be needed and the low vulnerability fuzes of the future are unlikely to be achieved by retrofit of existing fuzes.

4.4 DNBF and ADNBF

DNBF had been examined previously at MRL because it was a key intermediate to a number of primary explosives that were being prepared for assessment [11]. The conclusion from that study, mainly on the basis of impact and thermal sensitivity measurements, was that DNBF was a booster explosive similar to tetryl or unwaxed RDX. The VOD measurements in Table 6 support this conclusion; VOD is very similar to tetryl at the same diameter and %TMD [8b], and about 10% less than for similar RDX charges [8b]. The critical diameter is < 1.52 mm at 96.2 %TMD, while VOD for the 2.025 mm charge at 90.4 %TMD is only reduced by 4.5% from that at 12.75 mm diameter.

ADNBF is reported to be a relatively insensitive explosive with a high crystal density (1.902 Mg/m^3) [12]. Two problems were experienced in fabricating charges; very high pressing loads were needed to consolidate even to 90 %TMD, and the charges had poor mechanical integrity. All attempts to prepare 12.75 mm diameter charges resulted in fracture along planes parallel to the top/base upon ejection from the pressing mould, usually into 2-4 segments. Both problems have been informally relayed to one of the authors (RJS) by researchers at NWC China Lake, and can be overcome by incorporation of a polymeric binder.

The 5.95 and 4.05 mm diameter ADNBF charges have high VODs. The reduction of 9.2% in VOD when charge diameter is reduced from 5.95 to 2.025 mm diameter at 89.9 %TMD suggests that d_c is being approached; a reasonable estimate would be 1.5 - 2.0 mm.

Clearly ADNBF shows promise as an insensitive booster explosive. Insensitivity would need to be confirmed by appropriate hazard tests on formulations prepared using suitable binders. R & D is currently being carried out at NWC China Lake and development of this work should be followed.

4.5 Estimates of Critical Diameter

Throughout the text in Sections 4.2 - 4.4 comment has been made on d_c of the various explosives, with unexpected features being highlighted. Because there is so little data on d_c for unconfined charges at densities in the range 80 to 95 %TMD, the authors felt it worthwhile to highlight the estimates of d_c obtained in this study in a separate Table 7. The upper limit cited for d_c is the lowest diameter at which stable detonation was achieved. The lower limit was estimated in one of two ways:

(i) the highest diameter at which detonation failed, e.g. PBXW-7 at 90.0 %TMD, and RDX/PEW 94.6:5.4 at 88.9 %TMD, or

(ii) from the rate at which VOD was decreasing with diameter, it was possible to decide whether detonation failure was near, e.g. RDX/PEW 97.8:2.2 at 92.0 %TMD (see Fig. 6) and at 87.3 %TMD, and ADNBF at 89.9 %TMD. This permitted the decision that failure would occur within 0.5 mm of the highest diameter that detonation was achieved.

These results, while limited in their accuracy, are important both for engineering design in explosive trains, and for probing the mechanism of the detonation process. In particular, data are needed at densities typical of production explosives; extrapolation from data near crystal density (100 %TMD) can be quite misleading. For example, RDX/wax 92:8 is reported to have d_c < 2.2 mm at 99 %TMD (Table 1) whereas our data for 94.6:5.4 RDX/PEW at 88.9 %TMD indicates d_c > 4 mm, despite the lower wax content.

We intend to continue generating further much needed data.

5. Conclusions

An experimental technique for determining VOD on unconfined pressed booster explosives at small charge diameters has been developed. Components for the experimental method are readily fabricated and relatively easy to assemble.

VOD is determined using ultra-high speed streak photography, and stable/unstable detonation is assessed from the streak record. VOD is determined from the linear portion of the streak record, rejecting any initial part of the trace resulting from under or overdriving of the detonation by the EBW detonator.

Reproducibility of the system has been assessed as excellent, and there have been no unexpected failures even at a charge diameter of 1.52 mm. An unexpected source of inaccuracy has been detected resulting from a variation in magnification across the streak film. Further work is being carried out to quantify and remove this error, which can introduce inaccuracies of up to 3% in VOD. Smaller inaccuracies of up to 0.6% can also be introduced because of the difficulty of accurately determining the density of pressed pellets where the diameter is < 3 mm.

The experimental set-up was developed and proved on conventional RDX/PEW booster explosives. VOD was determined both as a function of diameter, and also as a function of PEW content for charges of 12.75 mm diameter.

A series of experimental firings was conducted on the US formulation PBXW-7 Type II which has been proposed by the US Navy as an insensitive booster explosive for fuzes. The VOD/diameter relationship was determined at both 80 and 90 %TMD, and d_c was estimated at both these densities. Comparison has been made with RDX/PEW formulations, and it is concluded that fuze redesign would probably be needed if PBXW-7 was substituted for tetryl or an RDX/wax formulation in a current service fuze.

VOD/diameter data were also generated for DNBF, a booster explosive typical of those currently in service, and ADNBF, a chemically related candidate insensitive booster explosive. DNBF has a VOD similar to tetryl at equal densities, and detonation is stable even at 1.52 mm diameter for 96.2 %TMD charges. ADNBF exhibited very promising VOD/charge diameter performance, and therefore progress on the US program on this explosive should continue to be followed.

Particular attention should be drawn to the estimates of d_c obtained in this work. Published data on d_c for the densities typically achieved in production filling (80-95 %TMD) are extremely limited, and a surprisingly large variation of d_c with %TMD was noted for several explosives. Further results are needed to supplement this extremely important data.

In summary, a method has been developed which permits ready measurement of VOD for unconfined booster explosives at small charge diameters and densities typical of those used in fuzes.

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7. References

1. Spear, R.J. and Davis, L.M. (1989). *An Australian insensitive munitions policy; a working paper prepared for Australian Ordnance Council* (MRL General Document MRL-GD-0020). Maribyrnong, Vic.: Materials Research Laborætory. A draft policy paper is expected to have been approved by the AOC for subsequent Service consideration in February 1990.

2. US Dept. of the Navy (1986). US Navy explosives policy on insensitive munitions. *OPNAVINST 8010.13A, 13 May 1986* (succeeds earlier OPNAVINST 8010.13).

3. US Dept. of the Navy (1985). *US Navy master plan for insensitive munitions program,* 1 April 1985, and references cited therein.

4. US Dept. of the Navy (1988). Technical requirements for insensitive munitions, *NAVSEAINST 8010.5B (in draft).* This will succeed NAVSEAINST 8010.5A of 10 September 1984, when issued.

5. Stosz, M. (1982). Development of new explosives for the US Navy. *ICT Internationale Jahrestagung,* Karlsruhe, FRG, p. 257.

6. Dagley, I.J., Spencer, H.J., Louey, C.N. and Parker, R.P. (1989). *An evaluation of ethylene-vinyl acetate copolymers as desensitizers for RDX in insensitive booster compositions prepared by the slurry coating technique* (MRL Technical Report MRL-TR-89-33). Maribyrnong, Vic.: Materials Research Laboratory.

7. Dagley, I.J., Montelli, L., Parker, R.P. and Louey, C.N. (1989). *Preparation, characterization and cookoff behaviour of booster compositions prepared from RDX and acrylic or ethylene-vinyl acetate dispersions* (MRL Technical Report MRL-TR-89-44). Maribyrnong, Vic.: Materials Research Laboratory.

8. Dobratz, B.M. and Crawford, P.C. (1985). *LLNL explosives handbook. Properties of chemical explosives and explosive simulants* (UCRL-52997, Change 2). Livermore, CA: Lawrence Livermore National Laboratory. a. Section 8.5, b. Section 19.

9. Spear, R.J., Nanut, V. and Dagley, I.J. (1986). *RDX-polyethylene wax formulations as potential replacements for tetryl in fuze leads, boosters and magazines* (MRL Report MRL-R-1015). Maribyrnong, Vic.: Materials Research Laboratory.

10. Baudler, B. and Montesi, L.J. (1986). *Qualification test results of PBXW-7 Mod I* (NSWC Technical Report NSWC/TR-86-22). Whiteoak, MD: Naval Surface Warfare Center.

11. Spear, R.J., Norris, W.P. and Read, R.W. (1983). *4,6-Dinitrobenzofuroxan, an important explosive intermediate* (MRL Technical Note MRL-TN-470). Maribyrnong, Vic.: Materials Research Laboratory.

12. Norris, W.P. (1984). *7-Amino-4,6-dinitrobenzofuroxan, an insensitive high explosive* (NWC-TP-6522). China Lake, CA: Naval Weapons Center.

13. Bobolev, V.K. (1947). *Dokl. Akad. Nank SSSR,* **57**, 789.

14. Dimza, G.V. (1976). *Combustion, Explosives and Shock Waves,* **12**, 216.

15. Price, D. (1970). Shock sensitivity, a property of many aspects. *Proceedings of 5th Symposium (International) on Detonation,* Pasadena, CA, p. 128.

16. Roslund, L.A. and Coleburn, N.L. (1970). Hydrodynamic behaviour and equation-of-state of detonation products below the Chapman-Jouguet state. *Proceedings 5th Symposium (International) on Detonation,* Pasadena, CA, p. 403.

17. Balyaev, A.F. and Sukoyan, M.K. (1961). *Combustion, Explosives and Shock Waves*, **3**, 19.

18. Campbell, A.W. and Engelke, R. (1976). The diameter effect in high-density heterogeneous explosives. *Proceedings 6th Symposium (International) on Detonation*, Coronada, CA, p. 642.

19. Campbell, A.W. (1984). *Propellants, Explosives and Pyrotechnics*, **9**, 183.

20. Dobratz, B.M., Finger, M., Green, L.G., Humphrey, J.R., McGuire, R.R. and Rizzo, H.F. (1979). *Selected sensitivity tests of triaminotrinitrobenzene (TATB) and TATB formulations and their evaluation* (UCID-18026). Livermore, CA: Lawrence Livermore National Laboratory.

21. Coleburn, N.L. and Drimmer, B.E. (1963). *Explosive properties of the amino-substituted symmetrical trinitrobenzene* (NOLTR-63-81). Whiteoak, MD: Naval Surface Warfare Center.

22. Murphy, M.F. and Coleburn, N.L. (1961). *A preliminary evaluation of Tacot, a new heat resistant explosive* (NOLTR-61-185). Whiteoak, MD: Naval Surface Warfare Center.

23. James, E., Jr. (1955). Charge preparation for precise detonation velocity studies. *Proceedings 2nd Symposium (International) on Detonation*, Washington, DC, p. 1.

24. Cook, M.A., Keyes, R.T., Partridge, W.S. and Ursenbach, W.O. (1957). *Journal of Chemical Physics*, **79**, 32, and other references cited therein.

25. Bonthoux, F., Deneuville, P. and de Longueville, Y. (1981). Diverging detonations in RDX and PETN based cast-cured PBX. *Proceedings 7th Symposium (International) on Detonation*, Annapolis, MD, p. 408.

26. Chick, M.C. and Learmonth, L.A. (1985). *Determination of shock initiation and detonation characteristics of PE4 in proof test geometries* (MRL Report MRL-R-979). Maribyrnong, Vic.: Materials Research Laboratory.

27. Parry, M.A. (1989). Unpublished data from studies at Materials Research Laboratory.

28. Cybulski, W.B., Payman, W. and Woodhead, D.W. (1949). *Royal Society of London, Proceedings*, **197**, 51.

29. Jaffe, I. (1960). *A method for determining the critical diameter of explosives* (NAVWEPS Report 7360). Whiteoak, MD: US Naval Ordnance Laboratory. [AD 252 875].

30. Zerilli, F.J. (1981). *Notes from lectures on detonation physics* (NSWC MP 81-399). Silver Spring, MD: Naval Surface Warfare Center. [AD-A119,865]. Lecture 4: Critical diameter and critical shock initiation pressure, by D. Price.

31. de Longueville, Y., Delclos, A., Gaudin, C. and Mala, J. (1981). Influence of inert binders on detonation properties of cast-cured PBX. *Proceedings 7th Symposium (International) on Detonation*, Annapolis, MD, p. 560.

32. Kipp, M.E. and Nunziato, J.W. (1981). Numerical simulation of detonation failure in nitromethane. *Proceedings 7th Symposium (International) on Detonation*, Annapolis, MD, p. 608.

33. Ramsay, J.B. (1985). Effect of confinement on failure in 95 TATB/5 Kel-F. *Proceedings 8th Symposium (International) on Detonation*, Albuquerque, NM, p. 6.

34. Spear, R.J., Wolfson, M.G. and Bentley, J.R. (1983). *Combustion and Flame*, **50**, 249.

35. Campbell, A.W., Malin, M.E., Boyd, T.J., Jr. and Mull, J.A. (1955). Technique for the measurement of detonation velocity. *Proceedings 2nd Symposium (International) on Detonation*, Washington, DC, p. 18.

36. Spear, R.J. and Nanut, V. (1987). *A comparative assessment of US and UK explosives qualified as replacements for tetryl* (MRL Report MRL-R-1094). Maribyrnong, Vic.: Materials Research Laboratory.

37. Wilson, W.S. (1978). *RDX/polyethylene wax compositions as pressed explosives* (MRL Report MRL-R-722). Maribyrnong, Vic.: Materials Research Laboratory.

38. Box, P., Wolfson, M.G. and Campanella, G.F. (1986). Velocity of detonation measurement of high explosives : present and future. *Proceedings 5th ANZAAS-AIST Conference on Science Technology*, Sydney, pp. 99-118.

39. Spear, R.J., Nanut, V., Redman, L.D. and Dagley, I.J. (1987). *Recommended replacements for tetryl in Australian production fuzes and related ordnance* (MRL Report MRL-R-1089). Maribyrnong, Vic.: Materials Research Laboratory.

40. Drimmer, B.E. (1983). *Navy bank of explosives data (NAVBED) Volume III (NSWC MP 83-230). Whiteoak, MD: Naval Surface Warfare Center.*

41. Hutchinson, C.D. (1985). *The response of intermediate explosives to thermal and shock stimuli*, PhD thesis, University of Cambridge, UK, Chapter 8.

Table 1 **Published Critical Diameters (d_c) for Pressed Explosives and Additional Data for Cast-cured and Extruded RDX Formulations**

	Formulation	Density (Mg/m^3) [%TMD]	d_c (mm)	Ref.
HBX-1	TNT/RDX/Al/wax 38:40:17:5	1.60 [90.9] 1.72 [97.7]	$\sim$ 6.35 $\sim$ 6	16 16
TNT	140 µm particle size 30 µm particle size	1.62 [98.0] 1.60 [97.0]	$\sim$ 3.25 $\sim$2.5	13 17
PBX-9404	HMX/NC/CEF 94:3:3	1.846 [99.0]	1.18 ± 0.02	18
PBX-9501	HMX/estane/BDNPA-F 95:2.5:2.5	1.832 [98.75]	< 1.52	18
PBX-9502	TATB/Kel-F 800 95:5	1.890 [97.3] 24°C 75°C -55°C	 $7.5 < d_c < 8$ $5.7 < d_c < 6$ $\sim$ 10.5	19
X-0219	TATB/Kel-F 800 90:10	1.930 [98.4]	15.0 ± 1.0	18
TATB	60 µm particle size 20 µm particle size	1.6 - 1.7 [82.6 - 87.7]	$6.35 < d_c < 9.53$ < 6.35	20
DATB		1.800 [98.0]	5.3	21
TACOT		1.45 [78.4]	3	22
RDX/wax	91.8:8.2	1.695 [99.0]	< 2.2	23
RDX	25-150 µm particle size1.00 [55.4][a]	$1.0 < d_c < 1.15$	13	
RDX/HTPB	88:12	1.63 [99.0][b]	$\sim$ 6	25
PE4	RDX/grease/PEDO 88:11:1	1.59 [98.1][a,c]	$2.6 < d_c < 4.0$	26
MEX	RDX/grease/plasticiser 88:6:6	1.4 [$\sim$ 86][c]	$5.5 < d_c < 6.0$	27

a. Lightly confined in plastic tubing.
b. Cast-cured charge.
c. Extruded charge.

Table 2 **VOD Measurements at Various Charge Diameters for RDX/Polyethylene Wax (PEW) Formulations Pressed to 92.0 %TMD**

	VOD (m/s) at Charge Diameter (mm)				
RDX/PEW Ratio	12.75	5.92	4.00	3.075	2.025
99.60:0.40	8537				
97.82:2.20	8297, 8252	8039	7968	7888	7208
97.15:2.86	8144, 8180				
95.33:4.69	8120				

Table 3 **VOD Measurements at Various Charge Diameters for RDX/PEW Formulations Pressed to Various %TMD**

		VOD (m/s) at Charge Diameter (mm)				
RDX/PEW Ratio	%TMD	12.75	5.92	4.00	3.075	2.025
99.60:0.40	88.9	8269				
95.33:4.69	88.9	7650				
94.59:5.39	88.9	7593 7567	6101	Fail		
97.82:2.20	87.3	7955	7380	6481	5440	Fail
	95.8		8465 8480	8455		8288

Table 4 VOD Measurements at Various Charge Diameters for PBXW-7 Type II Pressed to Nominally 90 and 80 %TMD

%TMD	VOD (m/s) at Charge Diameter (mm) 12.75	5.91	4.01	3.075	2.02
90.0	7783, 7691, 7894	7492, 7402, 7604	7398, 7444	7280	Fail
80.0	7319	6789		6329	
90.18	7590 (7349)[a]				
89.94	7426 (7364)[a]				
89.82	7469 (7300)[a]				

a Simultaneous measurement using ionisation probes.

Table 5 Literature data[a] for VOD for PBXW-7 (type) Formulations

Formulation	%TMD	VOD (m/s) at Charge Diameter (mm)		
		25.4	20.0	12.7
PBXW-7 Type I: TATB/RDX/Teflon[b] (60:35:5)	94.95	7669		
	91.95	7600		
	90.0			7350
	89.6	7660	7440[c]	
	77.6	6872		
BX4: TATB/RDX (10% HMX)/Teflon (60:35:5)	92.1	7795	7780	7695
	94.75			7780
BX3: BX4, replace Teflon with KEL-F 800	95.25			7790
BX2: TATB/RDX (5% HMX)/Teflon (60:35:5)	95.8			7780
BX1: BX2, replace Teflon with Kel-F 800	95.8			7780

a Data for PBXW-7 Type I are from ref. [40] and BX1-4 from ref. [41].
b Also reported to fail at 96.95 %TMD for diameter < 6.4 mm.
c Data for 19.2 mm diameter.

Table 6 **VOD Measurements at Various Charge Diameters for DNBF and ADNBF Pressed to Various %TMD**

Material	%TMD	VOD (m/s) at Charge Diameter (mm) 12.75	5.95	4.05	3.075	2.025	1.52
DNBF	96.2			7522		7480	7325
	94.5	7616	7535 7578	7458		6786	
	90.4	7422	7414	7449 7313		7092	
ADNBF	92.0			7814		7306 7433	
	89.9		7810	7718	Detonation[a]	7094	
	87.5		7426				

a Camera failure, no streak trace

Table 7 **Estimate of Critical Diameter (d_c) made from VOD/Diameter Measurements**

Explosive	%TMD	Critical Diameter (mm)
RDX/PEW 97.8:2.2	95.8	$d_c < 1.5$
	92.0	$2.0 > d_c > 1.5$
	87.3	$3.0 > d_c > 2.5$
RDX/PEW 94.6:5.4	88.9	$5.9 > d_c > 4.0$
PBXW-7 Type II	90.0	$3.0 > d_c > 2.0$
	80.0	$3.0 > d_c > 2.0$
DNBF	96.2	$d_c < 1.5$
	90.4	$d_c < 2.0$
ADNBF	92.0	$d_c < 2.0$
	89.9	$2.0 > d_c > 1.5$

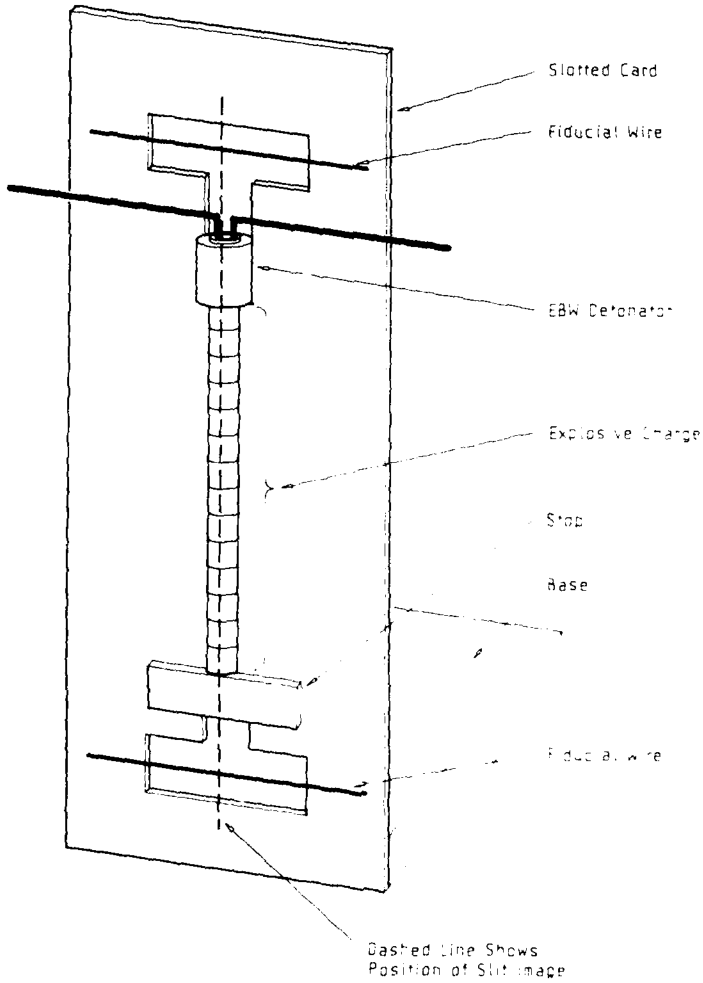
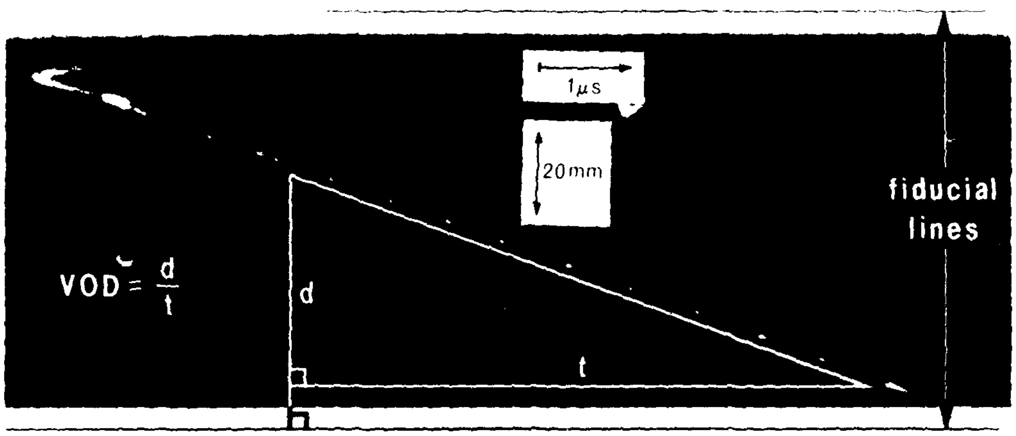


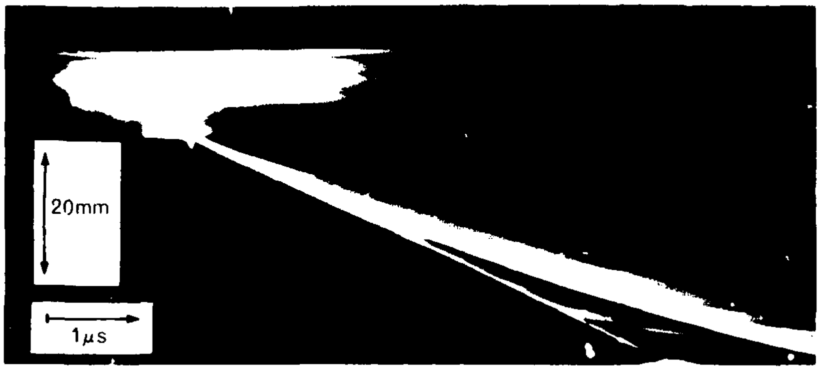
Figure 1 *Diagram of the test assembly used for determining VOD on a column of pressed explosive pellets. The streak camera slit is aligned to record along the dashed line as shown.*

(a)



(b)

Figure 2 *Examples of enlarged streak records*
(a) PBXW-7, 90.2 %TMD at 12.75 mm diameter. The charge was fired in air, with the streak image recorded on Kodak P3200 film. Simultaneous ionisation probe VOD measurement was carried out. VOD = 7590 m/s.
(b) RDX/PEW, 97.8:2.2, 92 %TMD at 5.92 mm diameter. The charge was fired in air with the streak image recorded on Kodak 2475 film. VOD = 8039 m/s. The bright spots correspond to the explosive pellet interfaces. The right-angled triangle has been superimposed to illustrate the VOD measurement method.



(a)

(b)

Figure 3 *Further examples of enlarged streak records.*
(a) PBXW-7, 90.0 %TMD at 3 mm diameter. The charge was fired in air and Kodak P3200 film was used. VOD = 7280 m/s.
(b) DNBF, 90.0 %TMD at 12.75 mm diameter. The charge was fired in argon and Ilford FP4 film was used. VOD = 7422 m/s.

Figure 4 *Example of enlarged streak record from a charge which failed to sustain detonation: PBXW-7, 90.0 %TMD at 2.02 mm diameter. The charge was fired in argon and Ilford FP4 film was used.*

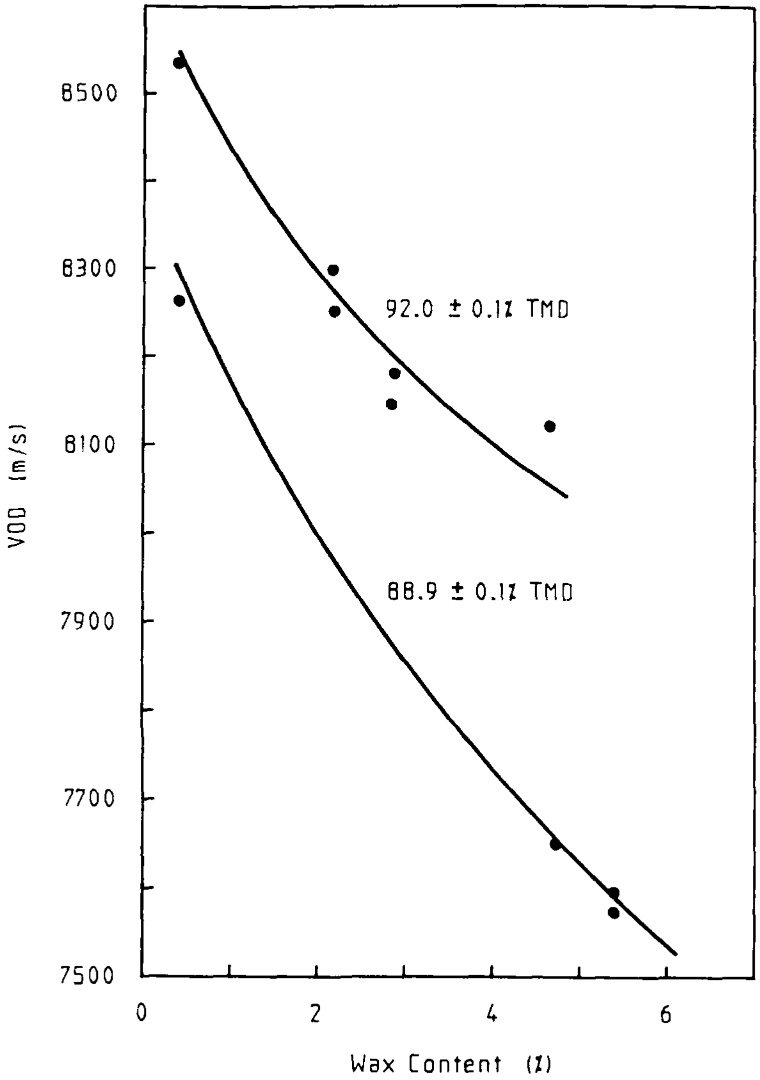


Figure 5 *VOD versus wax content for a series of RDX/PEW charges of 12.75 mm diameter, at 92.0 and 88.9 %TMD.*

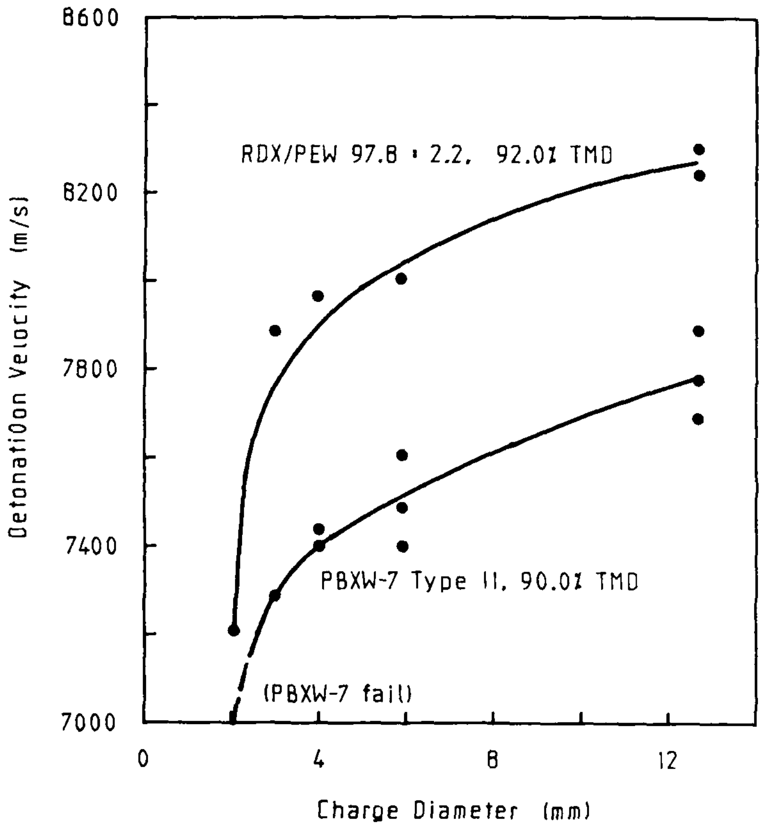


Figure 6 *VOD versus charge diameter for RDX/PEW 97.8:2.2 at 92.0 %TMD, and PBXW-7 Type II at 90.0 %TMD.*

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TITLE

Determination of detonation parameters of booster explosives at small charge diameters

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ABSTRACT

An experimental method for determining velocity of detonation (VOD) of unconfined explosives at small charge diameters has been developed. The experimental technique uses readily available components and is relatively easy to set up. VOD is measured by ultra-high speed streak photography; variation in magnification on the streak record has been detected. VOD was determined on conventional booster explosives based on RDX/polyethylene wax (PEW), DNBF, and two candidate insensitive booster explosives PBXW-7 and ADNBF. All were pressed to 80-95 %TMD (theoretical maximum density), and diameters ranged from 12.75 mm to 1.52 mm. A surprisingly strong dependence between the critical diameter (d_c) estimated from these firings and %TMD was observed. It is suggested that further measurements should be made for explosives pressed to 80-95 %TMD, which is typical of production filling and where only very limited data are available. Comment is made on the potential of PBXW-7 and ADNBF to replace conventional booster explosives in fuzes for insensitive munitions.

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